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THE ORIGIN OF RADIO EMISSION IN LOW-LUMINOSITY ACTIVE GALACTIC NUCLEI: JETS, ACCRETION FLOWS, OR BOTH?

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ABSTRACT

The low-luminosity active galactic nuclei in NGC 3147, NGC 4203, and NGC 4579 have been imaged at four frequencies with the Very Long Baseline Array. The galaxies are unresolved at all frequencies, with size upper limits of 10^3–10^4 times the Schwarzschild radii of their central massive black holes. The spectral indices between 1.7 and 5.0 GHz range from 0.2 to 0.4; one and possibly two of the galaxies show spectral turnovers between 5.0 and 8.4 GHz. The high brightness temperatures ($T_b \gtrsim 10^9$ K) and relatively straight spectra imply that free-free emission and/or absorption cannot account for the slightly inverted spectra. Although the radio properties of the cores superficially resemble predictions for advection-dominated accretion flows, the radio luminosities are too high compared to the X-ray luminosities. We suggest that the bulk of the radio emission is generated by a compact radio jet, which may coexist with a low radiative efficiency accretion flow.

Subject headings: accretion, accretion disks — galaxies: active — galaxies: individual (NGC 3147, NGC 4203, NGC 4579) — galaxies: nuclei — radio continuum: galaxies

1. INTRODUCTION

Most nearby normal and active galaxies with bulges appear to have supermassive black holes (BHs) at their centers (see Kormendy & Gebhardt 2001 for a review), although galaxies without bulges may lack BHs (Gebhardt et al. 2001). The central BHs are thought to power the low-luminosity active galactic nuclei (LLAGNs) in local Seyfert galaxies and LINERs. In a number of these LLAGNs, the radio emission is compact on milliarcsecond (mas) scales (Falcke et al. 2000; Nagar, Wilson, & Falcke 2001) when imaged with the Very Long Baseline Array (VLBA; Napier et al. 1993)[3]. They often have mildly inverted centimeter radio spectra with spectral indices $\alpha \approx +0.3$, where $S_\nu \propto \nu^\alpha$ (Wrobel & Heeschen 1991; Slee et al. 1994; Nagar et al. 2000). In our recent VLA study of the Palomar Seyfert sample (Ho, Filippenko, & Sargent 1997), we found that about half of the weak Seyferts selected by optical spectroscopy have flat or inverted radio spectra (Ho & Ulvestad 2001, hereafter HU01; Ulvestad & Ho 2001), These galaxies differ from more luminous Seyferts, which typically have optically thin synchrotron spectra with $\alpha \approx -0.7$ (Ulvestad & Wilson 1984, 1989; Ulvestad & Ho 2001). Possible explanations discussed by Ulvestad & Ho (2001) included free-free emission/absorption or an advection-dominated accretion flow (ADAF; see Narayan, Mahadevan, & Quataert 1998; Quataert 2001).

The Galactic Center source Sgr A* also has a mildly inverted spectrum at centimeter wavelengths, with $\alpha \approx +0.3$ from 1 GHz to over 100 GHz (Falcke et al. 1998). This spectrum is sometimes attributed to an ADAF (e.g., Narayan, Yi, & Mahadevan 1995; Manmoto, Mineshige, & Kusunose 1997). In ADAFs, synchrotron radiation from hot electrons in a $\geq 10^9$ K gas is self-absorbed, yielding a radio spectral index between +0.3 and +0.4 (Mahadevan 1997; Narayan et al. 1998). X-ray emission arises from Compton scattering or bremsstrahlung, but is far below the Eddington limit, since most of the plasma's energy is advected into the BH by the ions. The transition from a classical thin accretion disk to an ADAF takes place within $\sim 10^3-10^4$ Schwarzschild radii (R_S) of the BH. Compact radio emission from a number of LLAGNs has been attributed to ADAF processes similar to those inferred in Sgr A* (e.g., Fabian & Rees 1995; Mahadevan 1997; Ho et al. 2000; Wrobel & Herrnstein 2000). However, Di Matteo et al. (1999) find that the simplest ADAF models overpredict the radio and submillimeter fluxes in several nearby ellipticals.

Another possible model for Sgr A* and LLAGNs is that of a compact radio jet in combination with an ADAF (Falcke 1996; Falcke & Markoff 2000; Yuan 2000). As reviewed by Falcke (2001), the jet accelerates slightly due to a longitudinal pressure gradient, and integration of jet radio emission may result in a slightly inverted spectrum. Compton upscattering of the radio photons produces the X-rays. An energetically significant jet or outflow will reduce the accretion rate in the innermost region of the ADAF, which may explain the low level of radio emission seen in some ellipticals (Di Matteo et al. 1999; Quataert & Narayan 1999).

In this *Letter*, we report four-frequency VLBA imaging of three LLAGNs imaged previously at arcsecond resolution with the VLA (HU01). These galaxies were selected because they have inverted VLA spectra between 1.4 and 4.9 GHz and flux densities sufficiently high ($\gtrsim$10 mJy) for easy imaging with the VLBA. Therefore, they were good candidates for testing the various models that might account for their spectral shapes.

2. OBSERVATIONS AND RESULTS

The VLBA observed NGC 3147, NGC 4203, and NGC 4579 in March 2001 at central frequencies of 1.667, 2.271, 4.995, and 8.421 GHz. About six hours was spent integrating on each galaxy, divided among the four frequencies. Amplitude calibration used a-priori gain values together with system temperatures measured during the observations, and typically is accurate to 5%. Initial clock and atmospheric (phase) errors were derived from calibrator sources within 2°–4° of the galaxies,

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TABLE 1

VLBA OBSERVATIONAL RESULTS

Galaxy (1)	UT Date (2)	α(J2000) (h m s) (3)	δ(J2000) (° ′ ″) (4)	$S_{1.7}$ (mJy) (5)	$S_{2.3}$ (mJy) (6)	$S_{5.0}$ (mJy) (7)	$S_{8.4}$ (mJy) (8)	$T_{\rm b}$ (K) (9)	Calibrator (10)
NGC 3147	2001Mar10	10 16 53.6511	+73 24 02.695	7.0	6.8	8.8	9.3	$> 8.0 \times 10^8$	J1031+7441
NGC 4203	2001Mar19	12 15 05.0553	+33 11 50.384	6.2	7.4	9.5	10.0	$> 7.0 \times 10^8$	J1215+3448
NGC 4579	2001Mar26	12 37 43.5222	+11 49 05.488	18.3	21.1	22.8	19.3	$> 8.4 \times 10^8$	J1230+1223

NOTE.— Col. (1) Galaxy name. Col. (2) UT observing date. Col. (3)–(4) VLBA position. Col. (5)–(8) Flux densities at 1.7, 2.3, 5.0, and 8.4 GHz, respectively. Col. (9) Brightness temperature of the core. Col. (10) Calibrator source.

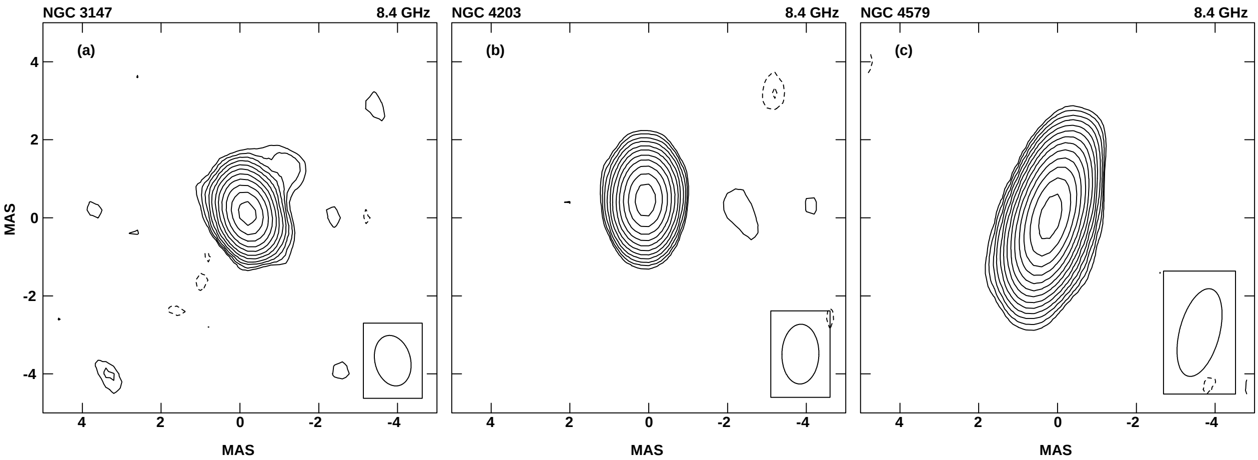

FIG. 1.— 8.4 GHz VLBA images of (*a*) NGC 3147, (*b*) NGC 4203, and (*c*) NGC 4579. All images are 9.6 mas on a side, with contour intervals increasing by factors of $\sqrt{2}$ from 0.25 mJy beam^{-1} (negative contours are shown dashed). The restoring beam for each image is shown in the lower-right corner.

using the technique of phase-referencing (Beasley & Conway 1995). This resulted in galaxy position errors of $\lesssim 1$ mas, dominated by uncertainties in the calibrator positions (from Johnston et al. 1995; A. J. Beasley et al., in preparation). The initial phase calibration was limited at low frequencies by the active ionosphere, and at high frequencies by the wet troposphere, but each galaxy was detected at all four frequencies. Phase self-calibration was applied iteratively, resulting in noise-limited images. Approximate beam widths ranged from ~ 7 mas at 1.7 GHz to 1.2 mas at 8.4 GHz, while the rms image noises were 90–150 μJy beam^{-1}.

Gaussian fitting showed that all VLBA images were dominated by a single unresolved component; we estimate size upper limits of half the beam widths. Derived flux densities are accurate to ~ 5% at 2.3 and 5.0 GHz, and ~ 10% (due to larger self-calibration corrections) at 1.7 and 8.4 GHz. Table 1 summarizes the observations and main results, and Table 2 lists some derived quantities and other pertinent information. Figure 1 shows the high-resolution, unresolved 8.4-GHz images of the galaxies, while Figure 2 compares the radio spectra with that of Sgr A*.

3. INDIVIDUAL GALAXIES

NGC 3147.—NGC 3147 contains a Seyfert 2 nucleus in an Sbc galaxy (Ho et al. 1997). The hard X-ray (2–10 keV) luminosity measured with *ASCA* is 3.4×10^{41}erg s^{-1} (Terashima, Ho, & Ptak 2000a), and observations with the *ROSAT* HRI (Roberts & Warwick 2000) show that this source is almost certainly located at the nucleus. Our upper limit to the source radius is $\sim$0.05 pc, or $\sim 1500 R_{\rm S}$ for a BH mass of 3.6×10^8 $M_\odot$. We estimated the BH mass using the tight empirical correlation between BH mass and bulge stellar velocity dispersion (Gebhardt et al. 2000; Ferrarese & Merritt 2000), adopting the $M_{\rm BH} - \sigma$ relation given by Gebhardt et al. (2000) and σ = 268 km s^{-1} from McElroy (1995)[4]. The VLBA flux densities of 7 and 9 mJy at 1.7 and 5.0 GHz can be compared to the VLA peak flux densities of 13 and 10 mJy at similar frequencies in late 1999 (HU01), so there may be weak 1.7-GHz emission on scales between tens of mas and 1 arcsec.

NGC 4203.—NGC 4203 is a nearly face-on S0 galaxy with a LINER 1.9 nucleus (Ho et al. 1997). It has a double-peaked broad Hα emission line with a full-width near zero intensity of at least 12,500 km s^{-1} (Shields et al. 2000), and a fairly weak nuclear X-ray source detected with *Chandra*, having $L_{\rm X}$(2–10 keV) = 5.0×10^{39} erg s^{-1} (Ho et al. 2001). For σ = 124 km s^{-1} (Dalle Ore et al. 1991), $M_{\rm BH} = 2.0 \times 10^7$ $M_\odot$. The upper limit for the source radius is $\sim$0.02 pc, or $1.0 \times 10^4 R_{\rm S}$, and the VLBA flux densities are consistent with the 1999 VLA peaks (HU01).

NGC 4579.—NGC 4579 is an SABb galaxy with a type 1.9 Seyfert or LINER nucleus (Ho et al. 1997). Its broad Hα line is double-peaked or double-shouldered (Barth et al. 2001), and it contains a variable hard X-ray source (Terashima et al. 2000b) with a 2–10 keV luminosity of $\sim 8.9 \times 10^{40}$ erg s^{-1} as measured

[4] Gebhardt et al. (2000) use $\sigma = \sigma_e$, the projected, luminosity-weighted velocity dispersion measured within the effective radius of the bulge. Since our objects do not have measurements of σ_e, we use $\sigma = \sigma_0$, the central velocity dispersion; Gebhardt et al. (2000) show that $\sigma_e \approx \sigma_0$ within a scatter of $\sim$10%.

TABLE 2
PROPERTIES OF THE RADIO CORES

Galaxy (1)	D (Mpc) (2)	$M_{\rm BH}$ ($M_\odot$) (3)	$\alpha_{1.7}^{5.0}$ (4)	$\alpha_{5.0}^{8.4}$ (5)	log $P_{8.4}$ (W Hz^{-1}) (6)	log $L_{8.4}$ (erg s^{-1}) (7)	log $L_{\rm X}$ (erg s^{-1}) (8)	log $L_{8.4}/L_{\rm X}$ (9)	log $L_{\rm bol}/L_{\rm Edd}$ (10)
NGC 3147	40.9	3.6×10^8	0.20 ± 0.10	0.11 ± 0.21	21.28	37.98	41.53	−3.55	−4.30
NGC 4203	9.7	2.0×10^7	0.38 ± 0.10	0.09 ± 0.21	20.05	36.76	39.69	−2.93	−4.42
NGC 4579	16.8	5.0×10^7	0.20 ± 0.10	-0.31 ± 0.21	20.81	37.52	40.95	−3.43	−3.80

NOTE.— Col. (1) Galaxy name. Col. (2) Distance from Tully 1988, who assumes $H_0 = 75$ km s^{-1} Mpc^{-1}. Col. (3) BH mass estimated from the $M_{\rm BH} - \sigma$ relation (see text). Col. (4) Two-point spectral index between 1.7 and 5.0 GHz. Col. (5) Two-point spectral index between 5.0 and 8.4 GHz. Col. (6) Monochromatic power at 8.4 GHz. Col. (7) Spectral luminosity at 8.4 GHz, $L_{8.4} \equiv \nu P_{8.4}$. Col. (8) X-ray (2–10 keV) luminosity (see text). Col. (9) Ratio of radio to X-ray luminosity. Col. (10) Ratio of bolometric luminosity (see text) to the Eddington luminosity.

with *Chandra* (Ho et al. 2001). The BH mass inferred from the $M_{\rm BH} - \sigma$ relation is $\sim 5 \times 10^7\ M_\odot$ (Barth et al. 2001). Our VLBA 8.4-GHz beam of 2.4 mas $\times$ 1.0 mas limits the source radius to $\sim$0.03 pc, or $\sim 6200R_{\rm S}$. The 1.7-GHz VLBA flux density is consistent with the previous VLA peak (HU01), while the 5-GHz value is considerably lower (22.8 mJy vs. 38 mJy). Falcke et al. (2001) found this galaxy to be variable at 15 GHz on time scales of 1–3 yr, so the change in the 5-GHz flux density over 17 months is most likely due to variability. This variability implies that the core spectral index changes over time, so model interpretations based solely on the spectral index must be made with caution.

4. IMPLICATIONS AND SUMMARY

What is the emission mechanism of the radio cores? In the Seyfert galaxy NGC 1068, Gallimore, Baum, & O'Dea (1997) resolved the flat-spectrum component S1 at 8.4 GHz using the VLBA; they attributed S1 to free-free emission from a parsec-scale torus. However, other flat-spectrum Seyfert cores are unresolved by the VLBA and appear to have other origins (Mundell et al. 2000). The free-free interpretation also is untenable for our sources because (1) they are much more compact ($r \lesssim 0.05$ pc) than the dimensions of nuclear tori and (2) they have brightness temperatures ($T_b \gtrsim 10^9$ K; Table 1) more than two orders of magnitude above the values expected for thermal emission. The relatively flat spectra over a factor of 5 in frequency (Fig. 2) seem to rule out free-free absorption as well, though NGC 4579 shows a slight spectral turnover above 5 GHz. Therefore, the prevalence of flat or inverted spectra in LLAGNs cannot, in general, be due to free-free emission or absorption. The brightness temperature limits are consistent with classical synchrotron self-absorption, although more than one self-absorbed component would have to be present, since self-absorbed synchrotron radiation from a single power-law distribution of electrons should result in $\alpha \approx 2.5$.

If our galaxies host massive BHs, as suggested by current BH demography studies and the evidence for nonstellar activity summarized in § 3, they must be radiating significantly below their Eddington limits. The nuclear bolometric luminosities of NGC 4203 and NGC 4579 are known from Ho et al. (2000) and Ho (1999), respectively. For NGC 3147, we assume $L_{\rm bol} = 6.7L_{\rm X}$(2–10 keV), empirically derived from an average of 10 objects analyzed by Ho (1999) and Ho et al. (2000). As shown in Table 2, all three objects are highly sub-Eddington systems: $L_{\rm bol}/L_{\rm Edd} \lesssim 10^{-4}$. In particular, they all lie comfortably within the expected value for ADAFs, which is estimated to be $L_{\rm bol}/L_{\rm Edd} \lesssim 10^{-2}$ (e.g., Narayan et al. 1998; Quataert 2001). Additional arguments for the existence of ADAFs in NGC 4203 and NGC 4579 are given in Ho et al. (2000) and Ho (2001), among them being the absence of the optical/ultraviolet continuum bump normally attributed to thermal emission from a thin disk. Thus, the compact radio cores could be emission from ADAFs. This is consistent with (1) the compactness of the sources ($r < 10^4R_{\rm S}$), (2) the apparent self-absorbed synchrotron nature of the emission, (3) the brightness temperature limits, and (4) the spectral indices[5].

Notwithstanding these arguments, the majority of the radio emission most likely does *not* come from accretion flows. We arrive at this conclusion by comparing the luminosity output of the radio and the X-ray bands. Table 2 shows that the ratio of the spectral luminosity at 8.4 GHz to the luminosity in the 2–10 keV band spans $3 \times 10^{-4} \lesssim L_{8.4}/L_{\rm X} \lesssim 1 \times 10^{-3}$. Yi & Boughn (1998) give a convenient expression for the relation between radio and X-ray luminosities in a standard ADAF model. Using our values of BH mass and X-ray luminosity in their Equation 2.10, we predict values for $L_{8.4}/L_{\rm X}$ that are $\sim$10 times smaller than the observed values. Hence our sources are overluminous in the radio compared to the X-rays. We note that this discrepancy is not alleviated by appealing to more recent variants of the ADAF model that incorporate outflows or convection (e.g., Quataert 2001). Either of these effects will suppress the radio component with respect to the X-rays (Quataert & Narayan 1999; Ball, Narayan, & Quataert 2001), exacerbating the problem. If the radio core were larger than in the canonical ADAF models, the surrounding X-ray bremsstrahlung region would be correspondingly larger, again increasing the discrepancy between our high observed values of $L_{8.4}/L_{\rm X}$ and the lower model values.

The most likely origins for the radio cores in our three galaxies are compact jets or outflows, as discussed by Falcke (2001) and Nagar et al. (2001). The high brightness temperatures, the flat/inverted spectra, and the compactness of the cores easily can be reproduced in such a model. However, it is unclear if the jet model can self-consistently explain both the radio and X-ray emission, let alone the entire spectral energy distribution. Falcke & Markoff (2000) successfully fitted the radio and X-ray spectra of Sgr A* with the jet model, but $L_{8.4}/L_{\rm X}$ in Sgr A*

[5] The apparent spectral turnover in NGC 4579, however, would require some modification of the standard ADAF model, such as inclusion of winds (Quataert & Narayan 1999).

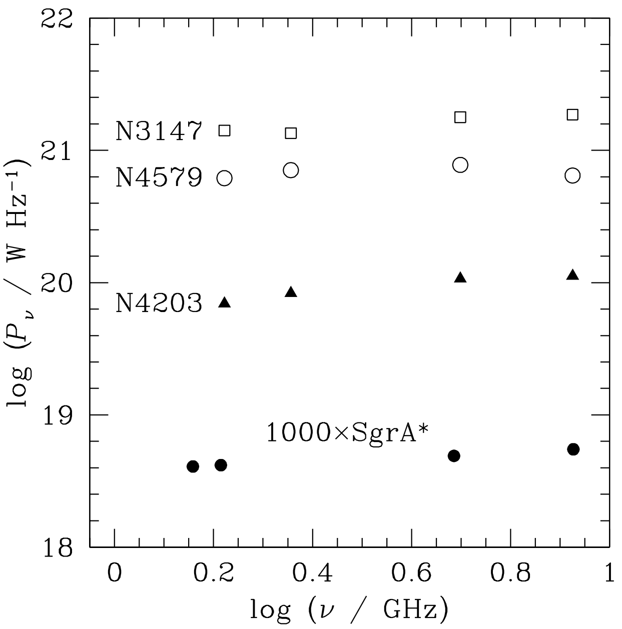

FIG. 2.— VLBA radio spectra of the unresolved cores of the three LLAGNs. The spectrum of the Galactic Center source Sgr A* (Falcke et al. 1998) is shown for comparison, assuming a distance of 8.0 kpc (Reid 1993), with power scaled up by a factor of 1000. Error bars for the powers are smaller than or equal to the symbol size.

is $\gtrsim$100 times higher than in our objects during the quiescent X-ray phase found by Baganoff et al. (2001). For a given radio jet power, the X-ray luminosities from self-Compton emission are well-constrained (e.g., Falcke & Markoff 2000), and are unlikely to contribute significantly in our galaxies.

A natural way to account simultaneously for the full spectral energy distribution of LLAGNs, such as those discussed here, is to incorporate facets of both classes of models discussed above, namely a jet and an ADAF (or some closely related variant of a low radiative efficiency accretion flow; see Quataert 2001). This is the approach taken by Yuan (2000), but we note that no existing model self-consistently incorporates both components.

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